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Analysis

Crop Production, Export of Virtual Water and Water-saving Strategies in Arizona

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ABSTRACT

Growing world population and the uncertain hazards that accompany climate change put an increasing pressure on the management and sustainability of scarce environmental resources, notably water. In spite of its water scarcity, the state of Arizona permits as much as 73% of its water to be consumed by a single sector, crop production. Since 79% of such crop production is not consumed in Arizona, it corresponds to exporting up to 67% of the water available in the state to the rest of the country and abroad. It has certain and glooming consequences on the availability of water for a state expected to see its population grow and its climate get drier. Based on input-output techniques, we simulate three scenarios aiming at saving 19% of the water available, a figure set by the first of them based on improving the efficiency of the current irrigation system. The same savings could also be reached by a twenty-seven-fold increase in the price of water or a 19.5% reduction in crop exports. Estimates indicate that the least costly solution is a more efficient irrigation system while export reduction is the second-best choice.

1. Introduction

Climate change and population growth are seen as two majors threats for water availability in arid and many semiarid regions (Christensen et al., 2004; Grimm and Fisher, 1992; Ribot et al., 2005; Vörösmarty et al., 2000). As such, several virtual water flow analyses have been performed on these regions to understand better the magnitude and nature of the imbalance between water use and water availability. Started during the 1980s when Israel realized that its agricultural export meant less of its scarce water was available for other uses (Allan, 1993, 1994; Allan, 1998; Fishelson, 1994), the concept of virtual water has since been applied to the regions of China (Guan and Hubacek, 2007; Han et al., 2014; Wang and Wang, 2009; Wang et al., 2013; Zhang et al., 2011b), the UK (Yu et al., 2010), and Spain (Cazcarro et al., 2013; Dietzenbacher and Velázquez, 2007; Lenzen, 2009; Velázquez, 2006) among others. The conclusions of the virtual water flow studies above highlight two important facts. First, irrational patterns of virtual water flows by which a water-scarce region is a net exporter of virtual water are not uncommon (Dietzenbacher and Velázquez, 2007; Finster, 1971; Guan and Hubacek, 2007). We call such patterns "irrational" because they go against the fundamental Heckscher-Ohlin principles of economic trade theory according to which a place should specialize in and export goods of which production factors are locally abundant. Second, once all the rounds of transactions necessary for the production of a commodity have been accounted for, agriculture is always found to consume a greater amount of water than either the industry or the services sectors (Velázquez, 2006; Zhang et al., 2011a; Zhang et al., 2011b; Zhao et al., 2010). Naturally, all such studies advocate for an improvement in the efficiency of water use in agriculture.

The paradox of water-scarce regions exporting water through their production and trade has also been highlighted in the U.S. For instance, Mubako et al. (2013) have analyzed the bilateral virtual water trade between California and Illinois across 8 sectors. Their article echoes the concerns expressed about California's water shortages and the even more dramatic drought of 2013–2014 (Howitt et al., 2014; Swain et al., 2014). Another recent contribution is Marston et al. (2015) who focus on groundwater originating from three aquifers (the High Plains, the Mississippi Embayment and the Central Valley) of which (over)exploitation for irrigation purposes may threaten national food security and be challenged by future droughts. Dang et al. (2015) take on a different approach by examining the virtual water content (VWC) for each food commodity group provided in the U.S. Commodity Flow Survey. When they compare it to the values at the international level,

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their results indicate that the VWC in the U.S. alone is as much as 51% of the international flows. It is much higher than the mass or value share of the U.S. market. The difference comes from the disproportionate amount of water-intensive meat commodities that are traded in the country.

In this paper, our aim is, first, to uncover how much water is embedded in the products and services made in Arizona and is "virtually" traded with its U.S. and foreign partners. Arizona is an interesting case in that it receives less media coverage than its drought-prone neighbor California; yet its water export was already pointed out as a critical issue by Finster (1971) more than three decades ago. The latter contribution focuses on the 1958 structure of Arizona's economy and on its trade pattern with the rest of the country. The author finds that, at that time, Arizona was a net exporter of 2.24 million acre-feet of water with respect to the rest of the U.S. but, unlike our paper, he does not highlight that agriculture is responsible for it. While a recent and rapid population growth (from 1.3 million in 1960 to 6.7 million today) has undoubtedly contributed to an increased demand for water, it is the well-developed agricultural sector of the State that takes the largest portion of responsibility for it. Using 35% of Arizona's land and having exports ranked 33rd in the nation in terms of value in 2012 (USDA, 2012), agriculture has been able to strive thanks to the water it has been diverting from the Colorado River for decades. Indeed, the lack of local rainfall and groundwater is compensated by artificial reservoirs and the Central Arizona Project. However, these heavy irrigation requirements impose huge water demand stresses on the ecological system of the State to the point where one has to wonder for how long crop production can keep engulfing 75% of the water used in Arizona (IMPLAN, 2010; USGS, 2010). This figure is disproportionally high since only 30% of the crops produced in Arizona are consumed locally, which implies that Arizona exports a significant amount of much-needed water.

As a result, the second objective of this paper is to determine whether significant water savings could be achieved through 1) a more efficient irrigation system, 2) an increase in the price of water, and 3) a reduction in crop exports. Beyond the logic of avoiding specialization and trade of goods of which production factors are not locally abundant (Heckscher and Ohlin, 1991), this exercise is motivated by three elements that may threaten the continuity of water availability. First, Arizona's population is expected to double by 2050 (AZDOA, 2012); second, various climate models anticipate more droughts in the state in the future (Dominguez et al., 2010) and, third, Arizona relies heavily on the Colorado River for irrigation surface water even when its source is located beyond the state's borders.

In order to investigate these issues and shed some lights into Arizona's current virtual water flows, we offer in Section 2 a review of the concept of virtual water flow, price elasticity and input-output model. Section 3 presents the economic and water data that are used in Section 4 to calculate the water content of Arizona's exports and imports. The results are provided across eight sectors of the state's economy. Section 5 reports the cost that three different water-saving strategies would have on the economy. Finally, the last section summarizes the most important results of this paper and provides some concluding remarks.

2. Methodology

2.1. The Concept of Virtual Water Flow and Economic Input-output Model

The input-output framework developed decades ago by Leontief (Leontief, 1964; Leontief, 1936) in that it allows consideration of both traded final goods (e.g. cattle) and also all intermediate goods (e.g. water and hay fed to cattle) used in the production process of the former, thereby avoiding the risk of double counting. This approach permits accurate measurement of the total amount of water embodied in trade. Virtual water is defined as the volume of water embodied in the production process of a good (Hoekstra and Hung, 2002). It is analogous to the 'water footprint' idea introduced later on by Hoekstra and Hung (Hoekstra and Chapagain, 2007), except that their study focuses on freshwater sources only and the national level.

Assuming n economic sectors in the local economy and noting x_i as the total output of sector i that satisfies intermediate demand of the sectors j (z_{ij}) and final demand f_i:

$$x_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{1}$$

Then we can denote the technical coefficients of production (a_{ij}) as z_{ij}/x_j. They correspond to the dollar value of z_{ij} needed for the production of \$1 of x_j. Eq.(1) can therefore be rewritten as:

$$x_i = \sum_{j=1}^{n} a_{ij}\, x_j + f_i \tag{2}$$

In matrix notation, Eq.(2) becomes:

$\mathbf{X} = \mathbf{AX} + \mathbf{f}$; hence,

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f} \tag{3}$$

where A is the direct input coefficient matrix and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is known as the *Leontief inverse matrix. The elements of* l_{ij} represent the total (direct and indirect) output of sector i that is required to satisfy \$1 of final demand in sector j.

In the input-output terminology, the amount of water used in the production process of a sector, noted $y_j = w_j/x_j$, is a direct water input coefficient. It allows us to calculate the quantity of water consumed by sector i to satisfy \$1 of final demand in sector j. The latter is called total (direct + indirect) water input coefficient or virtual water multiplier $\varepsilon_j = \Sigma_i y_i l_{ij}$.

2.2. Virtual Water Input-output Model and Price Elasticity

In order to calculate the virtual water flows associated to Arizona's (net) trade, we first define the direct water input coefficients of Arizona's imports as the technology, regulations and industry-mix of its trade partners may differ from its own. Let $\tilde{y}_j = \tilde{w}_j/\tilde{x}_j$ be the rest-of-the-U.S. (N) and rest-of-the-world (W) direct water input coefficients that we both approximate by the measurements on the U.S. as a whole. Since we have access to the list of imports of intermediate goods and of final goods (or institutional goods), we decide to report them separately. The net virtual water flows are thus $\sum_i y_j l_{ij} e_j - \sum_i \tilde{y}_j \tilde{l}_{ij} m_j$, where e_j is the amount of exports in sector j, m_j is the amount of imports in sector j and $\tilde{l}_{ij}$ is the ijth element of the Leontief inverse of the U.S. matrix. If we define the direct value-added coefficient as $va_i = v_i/x_j$ and the direct employment coefficient as $o_i = s_i/x_j$ then an decrease in crop exports leads to the following decreases in value added (Eq.4) and in employment (Eq.5):

$$\sum_i va_i l_{ij} (\Delta f_i^N + \Delta f_i^W) \tag{4}$$

$$\sum_i o_i l_{ij} (\Delta f_i^N + \Delta f_i^W) \tag{5}$$

Note that value added in Eq.(4) does not include employment compensation.

Ultimately, a lesser local production requires less imports. If we define the direct import coefficient as $ma_i = m_i/x_j$, then Arizona's regional trade balance can be define as:

$$\left(1 - \sum_i ma_i l_{ij}\right)(\Delta f_i^N + \Delta f_i^W) \tag{6}$$

Additionally, we develop below a set of equations based on a theoretical $\$1/m^3$ increase in the price of water as in an input-output framework the underlying assumption is that the physical unit of

measurement of a good corresponds to the amount that can be bought for $1 (Dietzenbacher and Velázquez, 2007). The equation indicating that the price ($1) of one physical unit of product j is equal to the cost of all the inputs necessary in its production is Eq.(8) below. It derives from Eq.(7) that reports the basic relationship implied in the column of the input-output table (with v_j the value-added in sector j).

$$x_j = \sum_i z_{ij} + \sum_i m_{ij} + v_j \tag{7}$$

$$\$1 = \sum_i a_{ij} + \sum_i (m_{ij}/x_j) + (v_j/x_j) \tag{8}$$

If we now introduce a cost $\hat{w}_j$ associated to the use of water in sector j, it will increase the price per unit of product j from its current level ($1) to a new level noted p_j. The same idea holds true for the input sectors i which are experiencing a new price per unit p_i. Assuming that imports and value-added are not modified by this local price increase, the (new) price still equals the costs per physical units:

$$p_j = \sum_i p_i a_{ij} + \sum_i (m_{ij}/x_j) + (v_j/x_j) + (\hat{w}_j/x_j) \tag{9}$$

If we subtract the new price p_j (Eq.9) with its former price (Eq.8), the price change of product j corresponds to:

$$p_j - 1 = \sum_i p_i a_{ij} - \sum_i a_{ij} + (\hat{w}_j/x_j)$$

$$\sum_i (p_i - 1) I_{ij} = \sum_i (p_i - 1) a_{ij} + (\hat{w}_j/x_j)$$

$$\sum_i (p_i - 1)(I_{ij} - a_{ij}) = (\hat{w}_j/x_j)$$

using matrix notation with e' as the summation vector composed of 1's and p' as the matrix of new price of one physical unit of product j, we can solve the linear equation above using $\mathbf{(I - A)^{-1} = L}$ to obtain Eq. (10):

$$\mathbf{p' - e'(I - A) = \widetilde{w}\hat{x}^{-1}}$$

$$\mathbf{p' - e' = \widetilde{w}\hat{x}^{-1}(I - A)^{-1}}$$

$$\mathbf{p' - e' = \widetilde{w}\hat{x}^{-1}L}$$

$$p_j = \sum_i (\hat{w}_j/x_j)\, l_{ij} + 1 \tag{10}$$

This relationship is also used in Dietzenbacher and Velázquez (2007) to measure the sensitivity of output prices to water use by sector.

3. Economic Structure and Water Use by Sector

Our input-output dataset comes from the Minnesota IMPLAN group and reports the transactions among 440 economic sectors defined in the North American Trade and Industrial Classification System (NAICS). Data on their exact amount of water used for consumption and/or production does not exist. Instead, we rely on the most recent USGS data (US Geological Survey). They correspond to the year 2010 and they became available in December 2014 (USGS, 2010). These water use data are estimated and published every 5 years and are not available at a finer level than the 8 sectors. They measure the amount of water withdrawal i.e., the quantity removed from the water source for a particular use regardless of how much of that total is consumptively used (USGS, 2010). Although USGS covers 8 types of water users, we aggregate some of them and work with 5 economic sectors because the "public supply" sector of USGS covers "users for domestic, commercial, and industrial purposes". The final matching and aggregating scheme is reported in Table A1 in the Appendix.

We rely on a closed input-output framework and the trade flow data of 2010 to capture the economic structure of Arizona's economy. Table 1 reports the direct and indirect input coefficients for each of the 5 sectors. They indicate the $ amount needed from each sector (by row) for the production of $1 of the sector of interest (by column) either directly or once all the rounds of transactions have been accounted for (i.e., indirectly). From this table, we note that crop production, like all the other sectors, depends primarily on the sector industry/services/domestic as it provides the necessary inputs such as fertilizers, machinery and workforce.

Table 1
Direct and indirect input coefficients.

Direct requirement matrix (Direct + Indirect requirement matrix)	Crop	Livestock/ aquaculture	Mining	Thermo-electric power	Industry/ services/ domestic
Crop	0.054 (1.071)	0.127 (0.175)	0.001 (0.009)	0 (0.006)	0.004 (0.017)
Livestock/ aquaculture	0.002 (0.015)	0.172 (1.222)	0 (0.008)	0 (0.006)	0.004 (0.018)
Mining	0.003 (0.057)	0.003 (0.064)	0.075 (1.114)	0.066 (0.095)	0.020 (0.075)
Thermoelectric power generation	0.015 (0.042)	0.016 (0.051)	0.009 (0.026)	2×10^{-6} (1.013)	0.011 (0.038)
Industry/services/ domestic/ wages	0.654 (2.367)	0.539 (2.587)	0.392 (1.448)	0.288 (1.070)	0.686 (3.381)
Sum	0.729 (3.552)	0.856 (4.099)	0.478 (2.605)	0.354 (2.189)	0.725 (3.530)

Source: As noted by an anonymous referee, the sectoral aggregation used here leads to assuming the same "technology" across the sectors that compose our eight final sectors. While aggregation likely yields upward biases in the general equilibrium estimates presented in Section 5, we also believe that the bias is not very large since 73% of the water goes to crop production.

Table 2 reports the economic structure and water use in Arizona with respect to the U.S. As expected, crop production is only a very small share of the state's output (0.6%) and it is a sector that is well connected to the rest of the economy: $1 spent in crop output generates $3.552 in the economy due to the direct, indirect and induced inputs (e.g., machinery, labor, fertilizer) needed in the production process (Miller and Blair, 2009) (see Table 1). These figures are in line with the national level. However, when it comes to water use, the difference is important: each dollar of crop produced in Arizona consumes 2.47 and 2.32 times more direct and total water than its national counterpart. The matching between the output of these economic sectors and the USGS water use data is described in SI 2 online. The amount of water withdrawals for crop production was m^3 6152 million in Arizona in 2010. It represents 51,532 gal of water per second. Columns 3–5 of Table 2 indicate that Arizona crops consume a share (73.13%) that is more than twice larger than its equivalent at the national level (30.7%) or nearly m^3 2.5/$1 of crop produced vs. m^3 1/$1 for the nation. The difference increases when the water-content of the inputs is also accounted for (m^3 2.671 vs. m^3 1.151 per $1 produced). Every $1 of crop produced in Arizona requires nearly 43 times the amount of water needed for $1 of production in the industry/services/domestic/wages sector. Contrary to general belief, the amount of water used to maintain golf courses (3% of the state's total. It is embedded in services) and for mining activities (1.42%) represents a very small share in comparison.

4. Location of Overall Final Demand and Net Trade Balance of Arizona

Furthermore, an analysis of the location of the consumers of goods and services made in Arizona reveals that the two most water intensive sectors, crops and livestock/aquaculture, are behind mining only in terms of the share of their output that is exported (79% and 45% respectively). Table 3 shows the amount and percentage of exports of

Table 2
Water use at the sectoral level in Arizona and the U.S. (2010).

		Output in $ million/year (% in parenthesis)	Sum of direct input coefficients	Sales multipliers (per $1)	Water use (ω_j) (million m^3/year) (%)	Direct water input coefficient y_j(m^3/$1)	Virtual water multipliers ε_i (m^3/$1)
Arizona	Crop	2480.21(0.60)	0.729	3.552	6152.89(73.13)	2.481	2.671
	Livestock/aquaculture	778.45(0.19)	0.856	4.099	102.63(1.22)	0.132	0.610
	Mining	7320.99(1.77)	0.478	2.605	119.77(1.42)	0.016	0.048
	Thermoelectric	5672.31(1.37)	0.354	2.189	144.32(1.72)	0.025	0.047
	Industry/services/ domestic/wages	397,429.06(96.07)	0.725	3.530	1893.54(22.51)	0.004	0.064
	Total	413,681.02 (100.00)			8413.14(100.00)		
U.S.	Crop	150,947(0.58)	0.745	4.963	151,517.17(30.70)	1.004	1.151
	Livestock/aquaculture	147,111(0.56)	0.668	4.407	15,788.40(3.20)	0.107	0.247
	Mining	435,087(1.66)	0.469	3.272	11,205.38(2.27)	0.026	0.064
	Thermoelectric	325,099(1.24)	0.606	4.087	221,925.96(44.97)	0.683	0.733
	Industry/services/ domestic/wages	25,093,057(95.95)	0.824	5.407	93,091.61(18.86)	0.004	0.078
	Total	26,151,301 (100.00)			493,528.52 (100.00)		

both output and virtual water from Arizona. The exports of crops represent only 0.47% of all goods made in Arizona, but the direct virtual water these exports carry with them is as much as 57.86% of the overall water available in Arizona (47.56% go to the rest of the U.S. and 11.30% to the rest of the world). Among the former sector, the top 4 agricultural products exported by Arizona in 2012 were cotton (40%), fruits & vegetables (fresh and processed, 34%), dairy (16%) and beef (10%) (Murphree, 2014). It means that even if agriculture consumes directly up to 73.13% of the water available in the state, only a mere 15.28% of that water stays in Arizona for final and intermediate consumption.

Table 4 reports the quantity of water associated to exports (see Eqs.4–6). Similar figures are reported for imports so that one can notice that, overall, Arizona has a net trade deficit but it is a net exporter of virtual water by around m^3 775 million. The average water content of $1 of its import ($m^3$ 0.023) is less than the water content of $1 of its export ($m^3$ 0.045). A deficit in trade and virtual water flow is observed for every single sector of the economy except crop where the greater water content of export (m^3 2.48/$1 vs. m^3 1.00/$1 for import) leads to the m^3 5.6 billion virtual water trade surplus. This gap could come from several factors such as differences in the mix of imported and exported crops, a less efficient use of water or higher level of evapotranspiration in Arizona than elsewhere. Therefore, we focus the next section on identifying a set of strategies that would lead to significant water savings in the state.

5. Defining and Selecting Water Saving Strategies

5.1. Scenario 1: Irrigation Technology Shifts to Less Water Intensive Irrigation

In light of the above results, one may wonder for how long the current levels and types of water use will last. Indeed, demand for water should increase as the forecasts predict around 5 million additional inhabitants in the state by 2050 (AZDOA, 2012), while, at the same time, the supply of water may be lesser and more uncertain than in the past due to the expected changes in the climate of the Southwest (Dominguez et al., 2010; Garfin et al., 2013). As such, we suggest three mitigation scenarios and measure their impact on the local economy. Our first water-saving scenario consists in switching from a gravity system to a pressure system that is more efficient and can be made of a low-flow or sprinkler system. In Arizona, 83.85% of the irrigated water is delivered through a gravity system (USDA, 2008) which is less costly and technologically advanced than a pressure system. However, it is

Table 3
Location of overall final demand for Arizona's products and for Arizona's water (Unit: $ million, m^3 million).

Sectors	Total		Consumption in Arizona		Exports to W		Exports to W		Total Exports	
	Output	Water use	Output	Water use	Output	Water use	Output	Water use	Output	Water use
Crop	2480.21	6152.89	518.06	1285.20	1578.86	3916.84	383.28	950.85	2480.21	6152.89
% by each sector	100.00	100.00	20.89	20.89	63.66	63.66	15.45	15.45	79.11	79.11
(% w.r.t the state)	(0.60)	(73.13)	(0.13)	(15.28)	(0.38)	(46.56)	(0.09)	(11.30)	(0.47)	(57.86)
Livestock/aquaculture	778.45	102.63	427.29	56.33	347.55	45.82	3.61	0.48	778.45	102.63
% by each sector	100.00	100.00	54.89	54.89	44.65	44.65	0.46	0.46	45.11	45.11
(% w.r.t the state)	(0.19)	(1.22)	(0.10)	(0.67)	(0.08)	(0.54)	(0.00)	(0.01)	(0.08)	(0.55)
Mining	7320.99	119.77	1386.28	22.68	4560.99	74.62	1373.73	22.47	7320.99	119.77
% by each sector	100.00	100.00	18.94	18.94	62.30	62.30	18.76	18.76	81.06	81.06
(% w.r.t the state)	(1.77)	(1.42)	(0.34)	(0.27)	(1.10)	(0.89)	(0.33)	(0.27)	(1.43)	(1.15)
Thermoelectric	5672.31	144.32	4361.17	110.96	1294.52	32.94	16.62	0.42	5672.31	144.32
% by each sector	100.00	100.00	76.89	76.89	22.82	22.82	0.29	0.29	23.11	23.11
(% w.r.t the state)	(1.37)	(1.72)	(1.05)	(1.32)	(0.31)	(0.39)	(0.00)	(0.01)	(0.32)	(0.40)
Industry/services/domestic/wages	397,429.06	1893.54	282,203.18	1344.55	89,657.21	427.17	25,568.67	121.82	397,429.06	1893.54
% by each sector	100.00	100.00	71.01	71.01	22.56	22.56	6.43	6.43	28.99	28.99
(% w.r.t the state)	(96.07)	(22.51)	(68.22)	(15.98)	(21.67)	(5.08)	(6.18)	(1.45)	(27.85)	(6.53)
Total	413,681.02	8413.14	288,895.98	2819.72	97,439.14	4497.38	27,345.90	1096.04	413,681.02	8413.14
% by each sector	100.00	100.00	69.84	33.52	23.55	53.46	6.61	13.03	30.16	66.48
(% w.r.t the state)	(100.00)	(100.00)	(69.84)	(33.52)	(23.55)	(53.46)	(6.61)	(13.03)	(30.16)	(66.48)

Note: % is by each sector, and (%) is with respect to the state.
Source: IMPLAN (2010).

Table 4
Direct and indirect Arizona trade flows and balances ($ million value and m^3 million in parenthesis).

Trade flows (Virtual water flows)	Crop	Livestock/ aquaculture	Mining	Thermo-electric	Industry/services/ domestic/wages	Total
Direct exports (Direct virtual water exports)	1962.15 (4867.69)	351.16 (46.29)	5934.71 (97.09)	1311.14 (33.36)	115,225.88 (548.99)	124,785.04 (5593.42)
Total exports (Total virtual water exports)	4234.28 (10,504.40)	2573.77 (339.31)	15,572.50 (254.77)	5945.88 (151.28)	405,122.68 (1930.19)	433,449.11 (13,179.94)
Direct imports (Direct virtual water imports)	2139.95 (2148.03)	1593.97 (171.07)	7994.48 (205.89)	–	116,126.70 (430.81)	127,855.10 (2955.81)
Total imports (Total virtual water imports)	4873.78 (4892.19)	4659.61 (500.08)	20,470.54 (527.21)	6045.84 (4127.14)	635,688.46 (2358.31)	671,738.3 (12,404.93)
Net trade balance: total exports − imports (Net virtual water trade balance)	− 639.50 (5612.20)	− 2085.85 (− 160.77)	− 4898.04 (− 272.44)	− 99.96 (− 3975.86)	− 230,565.78 (− 428.12)	− 238,289.12 (775.01)

also less efficient as it leads to water runoffs (USGS, 2016). A sprinkler system is not problem-free either as up to 35% of the water can be wasted because of evaporation and wind (USGS, 2000). When switching the irrigation system currently in use to the more efficient one for each type of crop and for the entirety of that crop, we find that a 19.17% decrease in the amount of irrigated water used can be achieved. This figure is based on the average irrigation water use data reported in USDA's Census of agriculture (2008) for each crop in the state of Arizona. Mathematically, it can be formulated as $\sum_{k=1}^{n}(\rho_{k,s_g} - \rho_{k,s_l}) \bullet r_k$, where ρ_k is the water use amount (m^3) per acre for crop k, s_g and s_l means gravity and low-flow system respectively, and r_k represents the area devoted to crop k's cultivation.

As shown in Table 5, most of the savings come from switching from a gravity system to a pressure system (18.25%) among the most water-intensive crops: alfalfa, cotton and wheat. Together they account for nearly 70% of the irrigated water use, hence even small gains in efficiency in the irrigation systems of these crops leads to large water savings in the state. The total water saving amounts to m^3 1018.05 million or $40.7 million based on the $0.04/$m^3$ rate used for agriculture that year (CAP, 2009). Based on the $158.04 per acre figure (USDA, 2008) for the state of Arizona, the pumping cost associated to a pressure system is estimated at $151.2 million in 2010 values, hence the cost of this scenario is estimated at $110.5 million. Our figure does not include additional costs related to the purchase of pipes, motors, electricity and other materials. However, the latter are relatively marginal and do not modify the overall difference with the magnitude of the cost calculated in the other two scenarios.

This irrigation technology shift is consistent with on-farm water saving strategies seen in other arid and semi-arid areas (e.g. Deng et al., 2006) because the expected gains in water use efficiency have already been documented in the literature. For instance, Dasberg and Or (1999) estimate that, in general, the water use efficiency of sprinklers is at 60–80%, the one of surface irrigation is at 50–60% while the one of drip systems (low-flow) is at 90%. Beyond technology switch, some contributions have emphasized the use of plastic mulch to prevent soil-evaporation (Zhang and Cai, 2001), to limit irrigation water supplement during the flowering and budding stages for cotton (Hu et al., 2001), and to rely on enforcement, regulation, and education to support

Table 5
Water use by crop types and reduction by irrigation system improvement (m^3 million value and % in parenthesis).

Crop types	Irrigated area (acre)	Water use (m^3per acre)				Current irrigation water use					Water use saving[c]		
		Gravity	Pressure	Low-flow	Sprinkler	Gravity	Pressure	Low-flow	Sprinkler	Total water use	Gravity to pressure	Sprinkler to low-flow	Total saving
Corn	44,578	5489	3392	–	–	152.74	60.02	–	–	212.76 (4.01)	58.48	–	58.48 (1.10)
Wheat	138,472	4440	3947	–	–	572.21	37.94	–	–	610.15 (11.49)	63.58	–	63.58 (1.20)
Alfalfa	280,741	7894	6044	–	–	1942.28	209.75	–	–	2152.04 (40.51)	455.22	–	455.22 (8.57)
Cotton	142,163	5920	–	4687	5550	744.04	–	31.36	54.43	829.82 (15.62)	155.01	8.47	163.47 (3.08)
Sorghum	24,328	4317	4070	–	–	87.09	16.91	–	–	104.00 (1.96)	4.98	–	4.98 (0.09)
Vegetables	102,471	3700	–	2960	4317	178.69	–	79.97	117.29	375.95 (7.08)	35.74	36.86	72.60 (1.37)
Orchards, vineyards, nut trees	30,745	8017	–	5551	7031	159.99	–	46.66	16.76	223.41 (4.21)	49.23	3.53	52.76 (0.99)
Other small grains[a]	6595	4194	5797	–	–	21.62	8.35	–	–	29.97 (0.56)	–	–	0 (0.00)
All other crops[b]	193,528	4410	3084	–	–	595.22	127.64	–	42.56	773.78 (14.57)	146.96	–	146.96 (2.77)
Total	963,621	5877	4157	3752	4576	4453.87	460.62	157.99	231.04	5311.88 (100.00)	969.19 (18.25%)	48.86 (0.89%)	1018.05 (19.17)

Data from USDA (2008) Census of Agriculture, 2008 FRIS – General Data 91, Table 28. Estimated Quantity of Water Applied and Primary Method of Distribution by Selected Crops Harvested: 2008 and 2003.

[a] A gravity system is more efficient for other small grains so we left it as such.

[b] Lettuce & romaine, and potatoes are missing data of each irrigation system, so removed in the calculation of water savings.

[c] Water saving of each crop is calculated by multiplying the irrigated area with the reduction of water use per m^3 switching from gravity to pressure/low flow or from sprinkler to low flow.

Table 6
Impact of a 19.5% decrease in crop export.

Impact of export decrease	Water use		Output		Value added[a]		Employment		Trade balance	
	m^3 million	% change	$ million	% change	$ million	% change	Number	% change	$ million	% change
Crop	− 1018.05	− 12.10	− 410.37	− 0.10	− 111.36	− 0.09	− 2488	− 0.08	− 193.24	− 0.05
Livestock/aquaculture	− 0.76	− 0.01	− 5.80	-1.40^{-3}	− 0.83	-0.69^{-3}	− 62	-1.95^{-3}	− 379.42	− 0.09
Mining	− 0.36	-4.27^{-3}	− 21.95	-5.31^{-3}	− 11.46	-0.96^{-3}	− 55	-1.73^{-3}	− 371.86	− 0.09
Thermoelectric	− 0.41	-4.87^{-3}	− 16.09	-3.89^{-3}	− 10.39	-0.87^{-3}	− 26	-0.83^{-3}	− 383.31	− 0.09
Industry/services/domestic/wages	− 4.32	− 0.05	− 907.37	− 0.22	− 254.94	− 0.21	− 7134	− 0.22	− 178.13	− 0.04
Total	− 1.023.90	− 12.17	− 1361.58	− 0.33	− 388.98	− 0.32	− 9765	− 0.31	− 1505.96	− 0.36

[a] Value added does not include employment.

farm-level water savings (Zhou, 2003).

None of the above options is easy to implement.For instance, Alcon et al. (2011) find that, in Spain, it took on average 20 years for farmers to shift from other types of irrigation to a low-flow (especially drip) irrigation system. Furthermore, the question of where the funding would come from is not obvious. Farmers already pay very little for water; hence they do not have strong incentives to fund new irrigation systems themselves. Should the government subsidize them (tax everyone) in the name of protecting the environment and guaranteeing water availability to future generations? Should city-dwellers be charged for on-farm water savings as additional supply should reduce the price of water for domestic usage? Answering these questions is beyond the scope of this paper and the rest of this section will limit itself to comparing the cost of the switch proposed so far with the cost of two other water saving strategies.

5.2. Scenario 2: Effect of a Water Price Increase on Output Prices

We use the 19.17% water-saving figure found in the previous scenario as the benchmark for our second scenario. Its driving force is an increase in the price of water which should lead to an increase in the price of the final agricultural goods and reduce their demand and output. According to CAP (CAP, 2009), the 2009/2010 delivery rates for water services were \$0.1/m^3 for municipal, industrial and federal usages, \$0.04/m^3 for agriculture and \$0.11/m^3 for all other usages in Arizona. Based on the traditional input-output assumption that the physical unit of measurement of a good corresponds to the amount that can be bought for \$1 (Dietzenbacher and Velázquez, 2007), we find that doubling the price of water used in agriculture would lead to a mere 10.8% increase in the price of locally-produced crops. But how much water would be saved? The literature finds that demand for irrigation water is generally inelastic to water prices in the short-run (Scheierling et al., 2006). However, water price elasticities have been reported in Moore et al. (1994) and Schoengold et al. (2006) for the long run. The first study calculates such elasticities across several types of crops in the Southwestern U.S.: − 0.3 for alfalfa, − 0.38 for corn, 0.17 for cotton, 0.02 for wheat, and − 0.2 for sorghum. Based on these measurements, we calculate that doubling the price of water to \$0.08/m^3 for these crops would lead to saving only 0.45% of the water devoted to crops each year (m^3 24 million). On the other hand, if we were to assume an average water demand elasticity of − 0.184for all types of crops as found in the latter study (Schoengold et al., 2006), we would conclude that a mere 0.74% water saving would occur. As a consequence, a 19% water saving would require the price of water to increase to 1.08 \$/m^3. It corresponds to about 27 times the current price. Such an increase in the price of water would cause the output price to be multiplied by 3.74 times (see Eq.(10)). Overall, this scenario corresponds to a cost worth \$8205.3 million for the crop sector, even when accounting for the water saving.

Even though it is clear that the expected magnitude of the cost associated to scenario 1 is lesser than that of scenario 2, we are aware that our latter measurement may be overstated. Indeed, since the production quantities are unitary price elastic in our approach, then the revenues are constant. As a result, when prices change, the quantities change in direct proportion. A computable general equilibrium model would be needed to circumvent this shortcoming and to consider indirect effects such as the possible substitution between local and foreign goods, a reduction in exports, the possible allocation of farm subsidies, and whether a change in the crop mix and/or in the efficiency of the irrigation system could happen. However, the full quantification of such effects would require the calculation of the associated elasticities for which data are non-existent. As a result, the scope of this paper does not include a CGE model.

5.3. Scenario 3: Direct and Indirect Arizona Trade Flows and Trade Balance Due to a Decrease in Agricultural Exports

Before we conclude, we investigate a third scenario which is based on the idea of conserving water by reducing the export of crop production (79%). In our input-output framework, a 19.17% water-use reduction in crop can be achieved by decreasing the current level of crop export by 19.5% (\$383 million) only. The negative effect on the state's output and value added would be relatively small at around 0.33% and 0.32%, which corresponds to \$1362 million and \$389 million respectively. In terms of employment, it would represent a mere 0.31% decrease (Table 6). Furthermore, the trade balance with the rest of the U.S. and of the world would be little impacted with a 0.36% (\$1506 million) decrease only (See Eq.6 and Table 6). These figures indicate that crop production is a very small share of the state's economy; yet, as seen earlier, it consumes a very large part of its water. We note also from Table 6 that the majority of these economic changes would not come from the crop sector itself but from the "industry/services/domestic" sector. The reason is that the crop sector needs more inputs from the latter sector than from any other sector to produce (see Table 1).

We should note that the effect on the net trade balance may be underestimated due to the partial equilibrium approach we have adopted here. In a CGE framework, one would see that a decrease in crop production would lead to an increase in local prices which could lead to a decrease in local crop consumption and/or an increase in crop imports from the rest of the U.S. or beyond. However, such an exercise, and the demand elasticities it relies on, is left for future research.

6. Conclusions

A virtual water flow analysis of the economic and trade structures of the state of Arizona allows us to uncover that crop production consumes as much as 73% of all the water used in the state. It is more than twice the national share. Furthermore, it turns out that the water embedded in crop production does not stay in Arizona for long: 79% of the crop is exported to the rest of the nation and abroad. It corresponds to exporting 67% of the state's water. Overall, Arizona is a net exporter of

virtual water because the water content of the crops it exports surpasses the one of the crops it imports. This apparent contradiction with well-established economic theory of specialization and trade motivates us to investigate three mitigation strategies aimed at preserving this scarce resource while harming the local economy little. All of them have figures set on saving 19% of the state's water as it is the upper threshold that can be reached in the first scenario. It consists in switching the current irrigation system from a gravity system or sprinklers to a pressure system or a low-flow system respectively. Such increase in water use efficiency is estimated to be much less costly than the other two water saving policies we investigate. Furthermore, some parts of Arizona have already completed significant steps to raise the water efficiency of their irrigation system (YAWC, 2015), but our findings indicate that there is still room for improvement. The other two, costlier, scenarios aim at achieving the same percentage of water saving but by increasing the price of irrigated water or by reducing the export of crops. The former is very unlikely as it requires a 27-fold increase in the price of water used for irrigation, which would put it above the price of any other usage. The latter scenario is more plausible considering that the 19.5% reduction in crop export it entails would still allow Arizona to export up to 59.6% of its crop production and the impact on each of the major macroeconomic variables (output, employment, value added and trade balance) would be around 0.3% only.

While our results clearly favor the approach of improving water use efficiency, we do not disregard the possibility that combining these three scenarios or complementing them with other approaches such as switching to less water-intensive crops (e.g. millet and sorghum that are well adapted to dry climate and erratic rains) could lead to an affordable solution as well. In either case the questions of who would pay for the change (farmers or customers), how (tax or subsidy) and for how long are important but are left for future research. Furthermore, water rights negotiated long ago (Dunning, 1977; Phare, 2009) and a well-developed network of lobbying are known to present various challenges to any of the scenarios offered here. However, one has to wonder how long it will take Arizona to value the risk mitigating potential of its water given its expected population growth, the low level of the Colorado river of which source is beyond the state's boundaries and the simplicity with which most crops grown in Arizona can be imported from well-rainfed U.S. states.

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Author Contributions

S. D. suggested the concept, designed the study and wrote the manuscript. J. B. collected the data, analyzed them and wrote the manuscript.

Competing Interests

The authors declare no competing financial interests.

Appendix A. Input-output Data Aggregation Process

The “public supply” sector of USGS covers “users for domestic, commercial, and industrial purposes”. The difference between the latter sector and the “domestic” and “industrial” sectors is unclear; hence we decide to aggregate them into a sector we call “Industry/services/domestic”. The irrigation sector originally defined by USGS includes crops as well as golf course, parks, turf farms and other landscape-watering. Our input-output dataset provides a very detailed classification with regards to crops (industrial sectors 1–10 in Appendix Table A1), but golf courses and others are integrated in sectors 406–410. Thus, we rename the “irrigation” sector as “crop” and merge the output and water requirement of the golf course sector in “Industry/services/domestic”. We rely on the National Water Information System (NWIS, 2010) to access information on water used by golf courses across 33 states and proxy the consumption across the 19 remaining states by using the average of the former.

It is important to note that the sector “Industry/services/domestic/wages” encompasses labor compensation by row and final demand by household by column. This choice is driven by the domestic usage of water embedded in the USGS classification. Moreover, while USGS separates water use by the “livestock” and “aquaculture” sectors, we aggregate them because industrial sector 14 “Animal production, except cattle and poultry and eggs” includes both livestock and fish farming (aquaculture).

Table A1
Aggregation scheme of USGS sectors.

USGS sectors	Description	IMPLAN sectors
Crop	Irrigation water use includes water that is applied by an irrigation system to sustain plant growth in agriculture. Irrigation water use includes self-supplied withdrawals and deliveries from irrigation companies or districts, cooperatives, or governmental entities.	1–10
Livestock/ Aquaculture	Livestock water use is water associated with livestock watering, feedlots, dairy operations, and other on-farm needs. The livestock category excludes on-farm domestic use, lawn and garden watering, and irrigation water use. Aquaculture water use is water associated with raising organisms that live in water—such as finfish and shellfish— for food, restoration, conservation, or sport. Aquaculture production occurs under controlled feeding, sanitation, and harvesting procedures primarily in ponds, flowthrough raceways, and, to a lesser extent, cages, net pens, and closed-recirculation tanks.	11–14
Mining	Mining water use is water used for the extraction of minerals that may be in the form of solids, such as coal, iron, sand, and gravel; liquids, such as crude petroleum; and gases, such as natural gas. The category includes other operations associated with mining activities.	20–30

Thermoelectric power	Water for thermoelectric power is used in generating electricity with steam-driven turbine generators. Since 2000, thermoelectric-power withdrawals have been compiled by cooling-system type. Thermoelectric power cooling water sources include fresh and saline water from both surface-water and groundwater sources.	31
Industry/services/ domestic/wages	Industrial withdrawals provide water for such purposes as fabricating, processing, washing, diluting, cooling, or transporting a product; incorporating water into a product; or for sanitation needs within the manufacturing facility. Public supply refers to water withdrawn by public and private water suppliers that provide water to at least 25 people or have a minimum of 15 connections. Public-supply water is delivered to users for domestic, commercial, and industrial purposes. Part of the total is used for public services, such as public pools, parks, firefighting, water and wastewater treatment, and municipal buildings, and some is unaccounted for because of leaks, flushing, tower maintenance, and other system losses. *Domestic deliveries represent the largest single component of public-supply withdrawals* Domestic water use includes indoor and outdoor uses at residences, and includes uses such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, watering lawns and gardens, and maintaining pools. Domestic water use includes potable and non-potable water provided to households by a public water supplier (domestic deliveries) and self-supplied water use.	15–19, 32–440, labor compensation/final demand by household

Note: description of each sector comes from USGS itself.

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